# Evaluating the flow stress of electrical steel under cold rolling in terms of the strain-rate hardening effect

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# Evaluating the Flow Stress of Electrical Steel under Cold Rolling in Terms of the Strain-Rate Hardening Effect

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**Abstract.** The flow stress of the Fe+3%Si electrical steel under actual cold rolling conditions is evaluated on the basis of the approximation of the existing data on the work hardening and strain-rate hardening of this steel during cold tensile testing. It has been discovered that ductility is significant during electrical steel cold rolling and, besides, that its value is lower for large strains and strain rates than for low strains and strain rates.

## INTRODUCTION

The modernization of the processes of cold deformation metal and alloys is currently related to the consideration of how the structure [1], crystallographic texture [2] and strain rate characteristics [3–7] affect the stress-strain state of these materials. The significance of strain rate in the cold upset forging of metals was first noted in [3]. Low-carbon steel hardening under cold compression for different strains and strain rates was studied in [4]. The strain-rate hardening effect of the Fe+1.70%Si+1.65%Mn alloy under cold rolling conditions with strains $\varepsilon \leq 0.15$ and strain rates $10^{-2} \leq \xi \leq 10^{3}\,\mathrm{s}^{-1}$ was studied in [5]. The strain-rate hardening effect for copper under tension was considered in [6]. The work hardening and strain-rate hardening effects of electrical steel Fe+3%Si under tension for strains $\varepsilon \leq 0.2$ and strains rates $\xi = 0.00015\ \mathrm{s}^{-1} \leq \xi \leq 1.1\ \mathrm{s}^{-1}$ at room temperature were reported in [7]. As follows from the study, the strain-rate hardening effect of the Fe+3%Si electrical steel can be considered under cold rolling conditions, as strain rate reaches large values (up to $1200\ \mathrm{s}^{-1}$) on modern cold rolling mills. However, there is no information on the value of flow stress of the Fe+3%Si electrical steel under any deformation processes pertaining to large strains and strain rates, when it would be possible to determine with a sufficient accuracy the flow stress value of the Fe+3%Si electrical steel under cold rolling conditions.

In this paper, applying the data from [7], we evaluate the work hardening and strain-rate hardening of the Fe+3%Si electrical steel in the actual cold rolling process.

## APPROXIMATION OF STRAIN AND STRAIN RATE DEPENDENCES OF FLOW STRESS FOR THE FE+3%SI ELECTRICAL STEEL

Figure 1 shows experimentally obtained [7] tensile curves for Fe+3%Si electrical steel samples strained up to $\varepsilon = 0.2$ with strain rates $\xi' = 0.00015\ \mathrm{s}^{-1}$ (curve 1) and $\xi'' = 1.1\ \mathrm{s}^{-1}$ (curve 2). Curves are plotted for flow stress $\sigma_f$. The values applying to strain rates $\xi'$ and $\xi''$ are marked with single and double primes respectively. The flow stress–strain curves (solid lines) corresponding to the tensile curves are shown in Fig. 2.

Strain and strain rate dependence of flow stress $\sigma_f$ under tension is approximated in the two-dimensional region ($0 < \varepsilon < 0.2$; $\xi' \leq \xi \leq \xi''$). For this purpose, the flow stress–strain curves are first approximated (Fig. 2) by the least-squares method using power functions. The resulting expressions are

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$$\sigma'_f(\varepsilon) = k'_0 + k'_1\varepsilon^{k'_2},\ \sigma''_f(\varepsilon) = k''_0 + k''_1\varepsilon^{k''_2}\ , \tag{1}$$

where the coefficients are as follows: $k'_0 = 489.7$ MPa, $k'_1 = 651.5657$ MPa, $k'_2 = 0.6702$, $k''_0 = 569.1$ MPa, $k''_1 = 740.962$ MPa, $k''_2 = 0.7876$. The approximating curves in Fig. 2 are drawn in dashed lines.

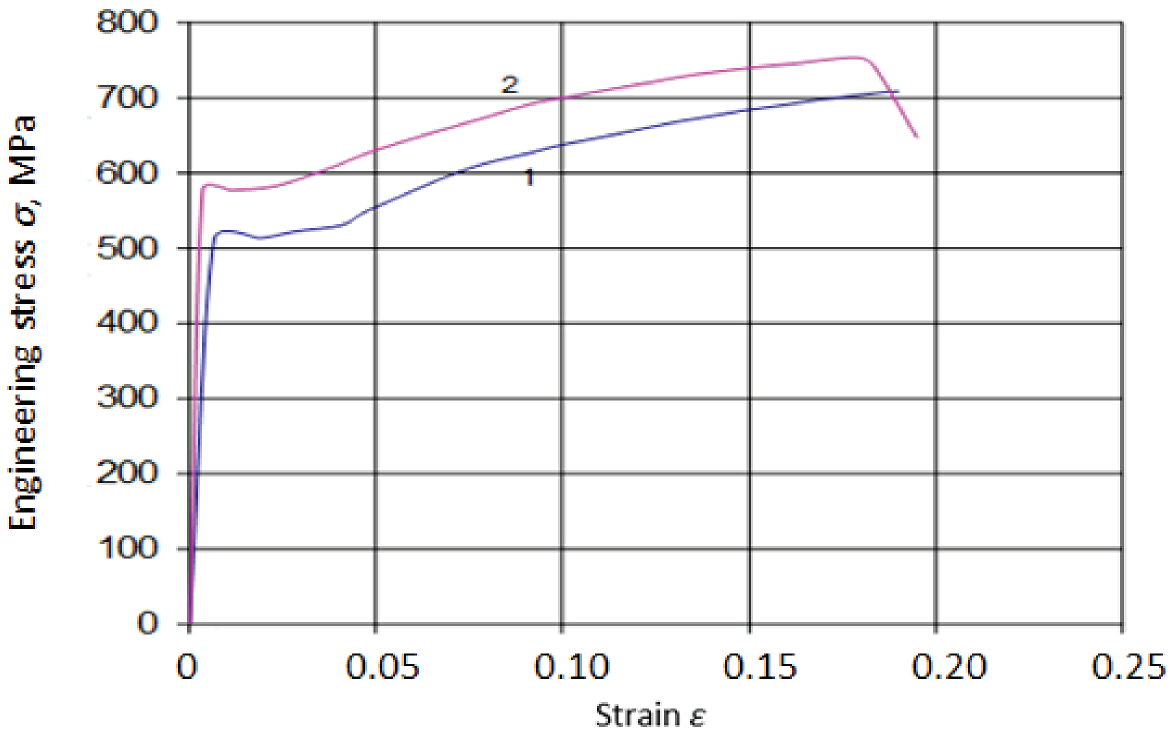


**FIGURE 1**. Stress-strain curves for Fe+3%Si samples under tension with strain rates $\xi = 0.00015$ $s^{-1}$ (1), 1.1 $s^{-1}$ (2) [7]

The strain rate dependence of flow stress for any strain $\varepsilon$ will be described by the function

$$\sigma_f = \sigma_0(\varepsilon) + m(\varepsilon)\ln\xi \tag{2}$$

proposed by A. Nadai [8] for hot metal deformation processes. Here, $\sigma_0(\varepsilon)$ is flow stress under static deformation, $m(\varepsilon)$ is a material-dependent coefficient. Expression (2) has a physical meaning only for strain rates not lying in a certain neighborhood of special strain rate $\xi = 0$.

Relationship (2) quite accurately describes the experimentally obtained dependence of $\sigma_f$ on $\xi$ at low strain rates for cold rolling of the Fe+3%Si alloy [7]. Moreover, it was established in [5] that strain-rate hardening remains finite for cold rolling of the Fe+1.70%Si+1.65%Mn alloy when $\varepsilon \le 0.15$ and $10^{-2} \le \xi \le 10^3$ $s^{-1}$. Relationship (2) satisfies this condition. In terms of physics, the choice of expression (2) can be explained by the effect of metal reheating owing to strain energy dissipation under cold rolling conditions. Indeed, if relying directly on the monitoring data from industrial rolling mills, it appears that, when the strip exit velocity is 250 m/min, metal temperature can reach 343–473 K (depending on the setup of the lubricoolant feed system in a rolling mill), which is certainly lower than the recrystallization temperature ranging from 873 K to 923 K. Furthermore, metal reheating increases with the rolling rate (strain rate), and this leads to additional metal softening.

Thus, the expression approximating the value of flow stress $\sigma_f$ for the steel under tension in the two-dimensional region ($0 < \varepsilon < 0.2$; $\xi' \le \xi \le \xi''$), is as follows:

$$\sigma_f(\varepsilon,\xi) = r_0(\varepsilon) + r_1(\varepsilon)\ln\xi\ , \tag{3}$$

where $r_0(\varepsilon) = [\sigma''_f(\varepsilon)\ln\xi' - \sigma'_f(\varepsilon)\ln\xi'']/k$, $r_1(\varepsilon) = [\sigma'_f(\varepsilon) - \sigma''_f(\varepsilon)]/k$, $k = \ln(\xi'/\xi'')$.

It should be noted that expression (3) differs from the corresponding expression for metal hardening under cold rolling conditions in [9] in that, in the latter study, the variables $\varepsilon$ and $\xi$ are separated and in expression (3) they are not.

In general, expression (3) gives only an approximate flow stress value (estimate) for the process of cold rolling of the Fe+3%Si steel. The fact is that steel hardening depends on strain, strain rate, hydrostatic pressure and the stress state type, which are different for tension and rolling [10]. Here is the data on strain and strain rate values for the actual cold rolling process of the Fe+3%Si steel. The second stage of the cold rolling of electrical steel after annealing under industrial conditions is performed in one pass with the following characteristics: work roll diameter $D = 290$ mm, initial strip thickness $h_0 = 0.70$ mm, final strip thickness $h_1 = 0.26$ mm, strip exit velocity $v_1 = 3.65$ m/s, linear velocity of the work rolls $v_r = 3.37$ m/s. In accordance with this data, the strain value amounts to $\varepsilon = 0.63$. It is assumed that plane strain occurs during strip cold rolling, and that is why the average strain rate is calculated by Trinks's formula [11]. The average strain rate is $\bar{\xi} = 265$ s$^{-1}$. One can see that, for the actual cold rolling process, the values of strain $\varepsilon$ and average strain rate $\bar{\xi}$ fall outside the limits of the previously considered region for the tension process. For the actual cold rolling process of the Fe+3%Si steel, expression (3) has the following flow stress value:

$$\sigma_f = 1150.172 \text{ MPa} . \tag{4}$$

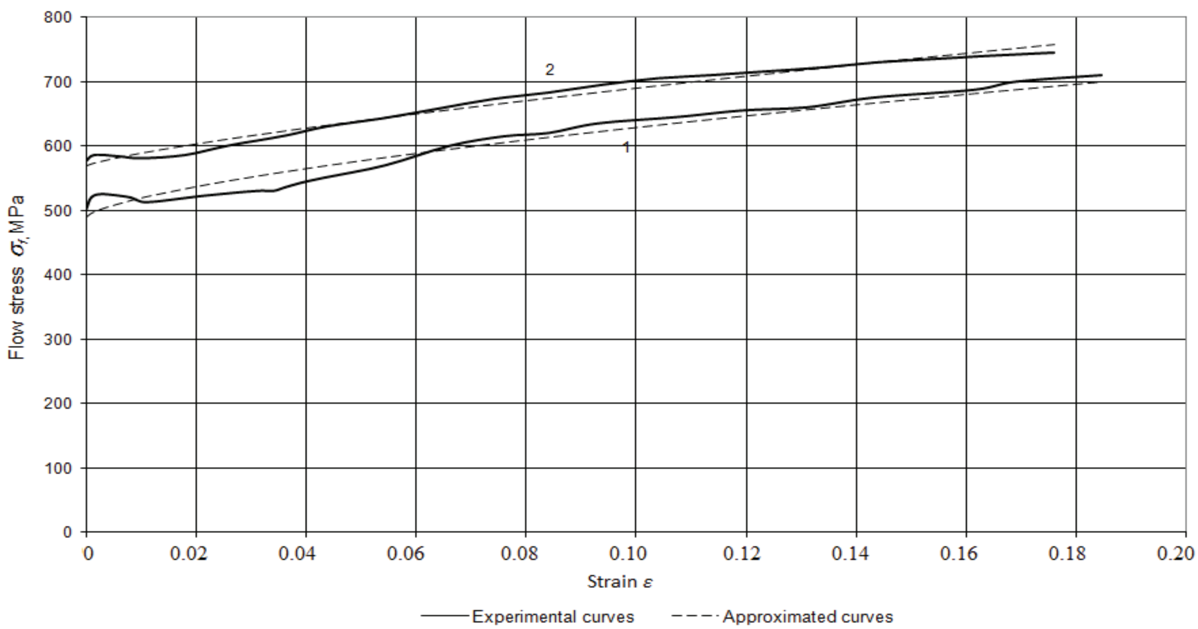


**FIGURE 2.** Flow stress–strain curves for electrical steel under tension with strain rates $\xi = 0.00015$ s$^{-1}$ (1), 1.1 s$^{-1}$ (2)

The flow stress of electrical steel under cold rolling conditions for the strain $\varepsilon = 0.63$ and low strain rate $\xi = 1.0$ s$^{-1}$ is

$$\sigma_f = 1077.079 \text{ MPa}. \tag{5}$$

It follows from (4) and (5) that, in this case, owing to strain-rate hardening, the flow stress increment value is

$$\Delta\sigma_f = 73.096 \text{ MPa} , \tag{6}$$

or 6.3%.

Thus, when analyzing the process of cold rolling of the Fe+3%Si steel, it is necessary to take into consideration the strain-rate hardening effect.

With the use of expression (3), the ductility $\mu$ of electrical steel, can be written as

$$\mu = dT/dH = r_1(\varepsilon)/\left(2\sqrt{3}\xi\right) , \tag{7}$$

where $T$ is the square root from the absolute value of the second deviatoric stress invariant, $H$ is the doubled square root from the absolute value of the second deviatoric strain rate invariant [10].

The ductilities of the electrical steel for the two above-mentioned rolling processes, found by expression (7), are, respectively,

$$\mu = 0.015 \text{ MPa·s} \tag{8}$$

and

$$\mu = 3.498 \text{ MPa·s}. \tag{9}$$

Thus, electrical steel ductility under cold rolling conditions for large strains and strain rates is lower in comparison with its value for low strains and strain rates. It corresponds to the results reported in [3] and [4] for low-carbon steel.

In conclusion, it should be noted that nowadays the error of the proposed procedure of evaluating the flow stress of the Fe+3%Si steel under cold rolling conditions cannot be determined on the basis of the dislocation concept of the deformation process [12]. This is due to the fact that that strain hardening is largely determined by such a structural parameter as the mean free path of dislocations, the physical interpretation of which is difficult. It follows that it is only possible to measure the flow stress approximation error (3) for cold rolling of the Fe+3%Si electrical steel experimentally.

## CONCLUSION

On the basis of existing experimental data, a formula has been found that approximates the strain and strain-rate hardening of the Fe+3%Si electrical steel during cold tensile testing. The formula was used for the evaluation of the flow stress of the Fe+3%Si electrical steel under actual cold rolling conditions in view of strain and strain-rate hardening. It has been demonstrated that strain-rate hardening has a considerable effect on the flow stress of electrical steel during cold rolling. It has also been found that steel ductility for large strains and strain rates is low in comparison with its value for low strains and strain rates.

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